FREQUENCY STABILITY REQUIREMENTS FOR NARROW BAND RECEIVERS

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Abstract

Very-narrow-band Global Positioning System (GPS) receivers have recently been proposed in order to help mitigate the effects of scintillation. This paper will revisit the stability requirements placed on the local oscillator of such receivers.

INTRODUCTION

The need to have good local oscillator short- and medium-term stability for phase tracking receivers has been well documented, especially for space communications [1]. Recently there has been great interest in improving the tolerance of WAAS/GPS Reference Station receivers to the effects of ionospheric scintillation in order to improve their robustness. One means that has been suggested to accomplish this is to narrow the bandwidth of the receiver. Morrissey et al. [2] undertook a study to quantify scintillation effects, through simulation, on a WAAS reference receiver in order to determine optimum estimates for certain key parameters, such as loop bandwidth, discriminator type, and tracking loop order that would maximize performance of the receiver.

However, one parameter that was not varied or simulated in their study was local oscillator stability. Obviously, this was because an atomic frequency standard, similar to the one used at the WAAS Reference Stations, was used as the local oscillator for the receiver being tested. But it must be kept in mind that the short-term performance of a local oscillator plays a more significant role when estimating the performance of a narrow bandwidth receiver than long-term performance. It should also be kept in mind that the short-term performance of an atomic frequency standard depends solely on the performance of the crystal oscillator selected by the manufacturer of the atomic frequency standard. The short-term performance of an

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **Frequency Stability Requirements for Narrow Band Receivers**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Innovative Solutions International,1608 Spring Hill Road Suite 200,Vienna,VA,22182**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001509. 32nd Annual Precise Time and Time Interval (PTTI) Meeting, 28-30 Nov 2000, Reston, VA

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

atomic frequency standard will be dominated by the performance of the crystal for up to several seconds, depending on the attack time of the cesium standard in question.

Studies by Van Dierondonck and Hua [3] have shown that selection of a local oscillator for a Scintillation Monitor Receiver is very critical to its performance. Several types of ovenized crystal oscillators of different cuts (SC and AT) and different fundamental frequencies were evaluated before one was chosen for their purposes.

The use of receivers with narrower bandwidths seems to be on the increase for many applications. Therefore, it was thought that a short note showing the effects of oscillator stability, more properly instability, on receiver phase-lock loop (PLL) performance would be helpful. It is noted that PLL performance is linked directly to oscillator performance. Several types of input disturbances cause a certain jitter in the error detector of the tracking loops. It has been observed that PLL tend to loose lock when the phase jitter out of the error detector exceeds 1 radian [4].

MEASUREMENT ERRORS

The dominant sources of phase error in a GPS receiver PLL are phase jitter and dynamic stress error [5]. The 3σ values of this PLL error and its rule-of-thumb tracking threshold are computed by:

$$3\sigma_{PLL} = 3\sigma_j + \theta_e < 45^\circ \tag{1}$$

where:

σ_j = 1σ phase jitter from all sources except dynamic stress error, and
θ_e = dynamic stress error in the PLL tracking loop.

Equation (1) shows that the dynamic stress error is a 3σ effect and is additive to the phase jitter. The phase jitter is the root-sum-square of every source of uncorrelated phase error, such as thermal noise and oscillator noise. Oscillator noise includes both jitter induced by vibration and jitter caused by oscillator instability. The 1-sigma (σ) rule of thumb for the PLL tracking error is given by:

$$\sigma_{PLL} = \sqrt{(\sigma_t{}^2 + \sigma_v{}^2 + \sigma_A{}^2)} + \theta_e/3 \leq 15^\circ \tag{2}$$

where:

σ_t = 1-sigma thermal noise in degrees,
σ_v = 1-sigma vibration-induced oscillator jitter in degrees, and
σ_A = Allan-variance-induced oscillator jitter in degrees.

Fuchser [4] has shown that the equation for the short-term Allan variance for a second-order PLL is

$$\sigma_A(\tau) = 2.5(\Delta\theta/\omega_L\tau) \tag{3}$$

where:

$\Delta\theta$ = root mean square jitter into phase discriminator due to oscillator (rad),
ω_L = L-band input frequency = $2pf_L$ (rad/sec), and
τ = short-term stability gate time for Allan variance measurement (sec).

The equation for a third-order PLL is similar:

$$\sigma_A(\tau) = 2.25(\Delta\theta/\omega_L\tau) \tag{4}$$

If the Allan variance has already been determined for an oscillator for the short-term gate time, t, then the Allan-deviation-induced jitter in degrees can be computed from the above equations. The short-term gate time used in the Allan variance measurement must be evaluated at the noise bandwidth of the carrier loop filter τ = 1/B_n. Rearranging terms, we get for a second-order PLL:

$$\theta_{A2} = 144(\sigma_A(\tau)f_L/B_n \; deg \tag{5}$$

and for a third-order PLL, we get:

$$\theta_{A3} = 160(\sigma_A(\tau)f_L/B_n) \; deg. \tag{6}$$

OSCILLATOR INSTABILITY

In order to evaluate Equations (5) and (6), data for a number of oscillators was obtained from [6] and manufacturer's specifications. Data obtained from [6] were for a poor quality crystal and a high quality crystal. The specifications for one manufacturer of a cesium frequency standard also contained the short-term performance of its crystals. Its performance fell in between that of the high and poor quality crystals, as indicated in Figure 1. The specifications of a second manufacturer did not contain the short-term performance of its crystals used in its standard, but it is assumed that it would be comparable in performance to that of the other manufacturer. The data used in this study are shown in Table I. Figure 1 is a plot of these values.

Tau	Log (tau)	Cesium A	Standard Cesium B	High Perf. Cesium B	Good XO	Poor XO
0.001	-3		1.0E-09	1.0E-09	5.0E-11	8.0E-08
0.01	-2		7.5E-11	7.5E-11	5.0E-12	9.0E-09
0.1	-1		1.2E-11	1.2E-11	5.0E-13	5.0E-10
1	0	2.0E-11	1.2E-11	5.0E-12	1.0E-13	5.0E-11
10	1	2.1E-11	8.5E-12	3.5E-12	1.0E-13	5.0E-11
100	2	5.0E-12	2.7E-12	8.5E-13	5.0E-13	5.0E-11
1000	3	1.6E-12	8.5E-13	2.7E-13	7.0E-13	1.0E-10
10000	4	5.0E-13	2.7E-13	8.5E-14	5.0E-12	3.0E-10

Table I - Sigma (Allan variance) for various values of tau (interval) for five different kinds of frequency standards. These include a high quality crystal oscillator, one of not so good a quality, a cesium frequency standard from one manufacturer, and two cesium frequency standards for a second manufacturer, one a high performance standard and one a normal standard.

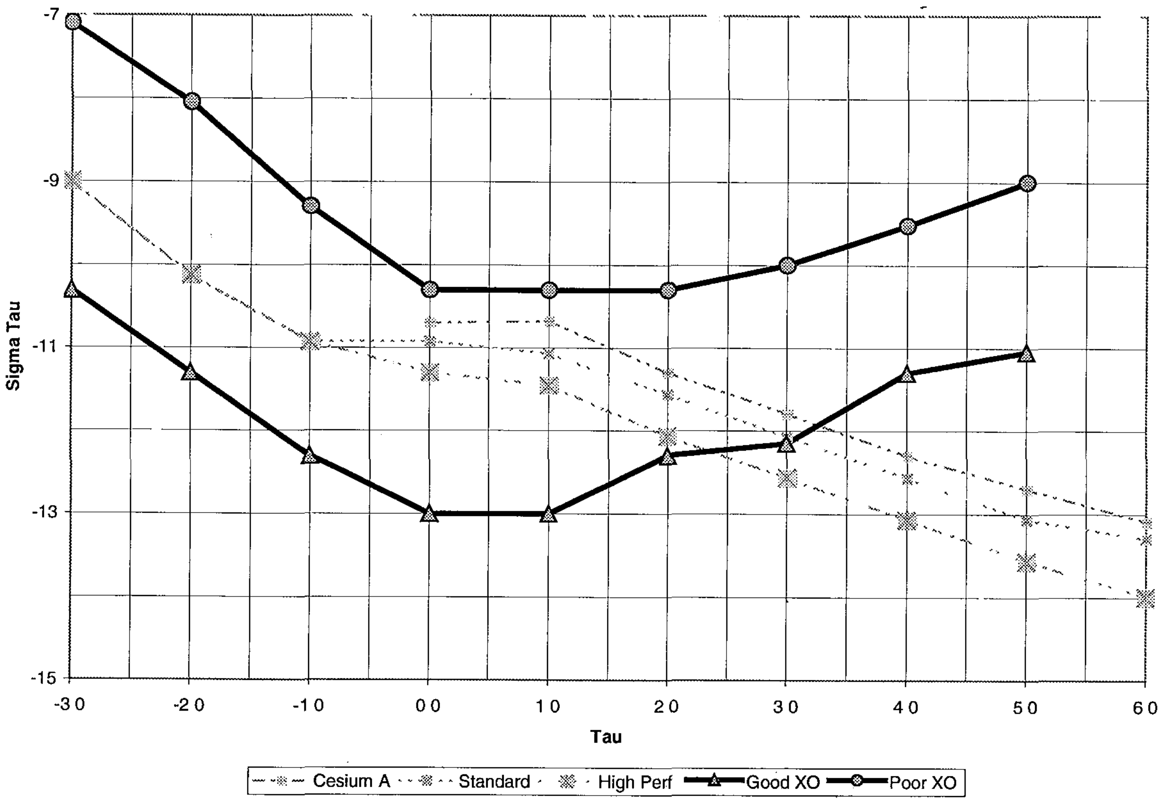

Figure 1 - Graph of the Allan variances for five different kinds of frequency standards. These include a high quality crystal oscillator, one of not so good a quality, a cesium frequency standard from one manufacturer, and two cesium frequency standards for a second manufacturer, one a high performance standard and one a normal standard.

DISCUSSION

Values of the Allan variance for a representative number of samples corresponding to various values of receiver bandwidth were derived from the tabular data contained in Table I. Tables II-V show the values of the Bandwidth for which the values of τ and the corresponding values

Bandwidth	Tau	L1 High	Theta A 2 Med	Poor
15	0.07	0.018	0.358	**22.063**
10	0.10	0.011	0.272	**11.344**
5	0.20	0.019	0.494	**17.571**
3	0.33	0.025	0.724	**20.828**
1	1.00	0.023	1.134	**11.344**
0.2	5.00	0.113	**5.672**	**56.719**
0.05	20.00	2.202	**4.274**	**213.201**

Table II - Values of the Allan-variance-induced oscillator jitter. Values were computed for a second-order PLL (θ_{A2}) and the GPS L1 frequency using Equation (5).

of the Allan-variance-*induced oscillator jitter* were computed using Equations (5) and (6). The computations were done for second- and third-order PLL and both GPS frequencies, L1 and L2.

Bandwidth	Tau	L1 High	Theta A 3 Med	Poor
15	0.07	0.020	0.398	**24.515**
10	0.10	0.013	0.302	**12.604**
5	0.20	0.021	0.549	**19.523**
3	0.33	0.028	0.804	**23.142**
1	1.00	0.025	1.260	**12.604**
0.2	5.00	0.126	**6.302**	**63.021**
0.05	20.00	2.447	**4.748**	**236.890**

Table III - Values of the Allan-variance-induced oscillator jitter. Values were computed for a third-order PLL (θ_{A3}) and the GPS L1 frequency using Equation (6).

Bandwidth	Tau	L2 High	Theta A 2 Med	Poor
15	0.07	0.014	0.279	**17.192**
10	0.10	0.009	0.212	**8.839**
5	0.20	0.015	0.385	**13.691**
3	0.33	0.019	0.564	**16.229**
1	1.00	0.018	0.884	**8.839**
0.2	5.00	0.088	**4.420**	**44.197**
0.05	20.00	1.716	3.330	**166.130**

Table IV - Values of the Allan-variance-induced oscillator jitter. Values were computed for a second-order PLL (θ_{A2}) and the GPS L2 frequency using Equation (5).

Bandwidth	Tau	L2 High	Theta A 3 Med	Poor
15	0.07	0.015	0.310	**19.102**
10	0.10	0.010	0.236	**9.821**
5	0.20	0.016	0.428	**15.213**
3	0.33	0.022	0.627	**18.032**
1	1.00	0.020	0.982	**9.821**
0.2	5.00	0.098	**4.911**	**49.107**
0.05	20.00	1.906	3.700	**184.589**

Table V - Values of the Allan-variance-induced oscillator jitter. Values were computed for a third-order PLL (θ_{A3}) and the GPS L2 frequency using Equation (6).

From Tables II-V it is obvious that the values of the oscillator-induced jitter arising from the poor crystal oscillators is greater than 15 degrees. This amount of jitter should be sufficient to cause the receiver carrier-tracking loop to lose phase lock. It should be pointed out that the oscillator-induced jitter is a very small order effect to the code tracking loop and that both the code and carrier tracking loops must be tracking in order for a GPS receiver to maintain lock.

However, it is not immediately obvious that the listed amount of oscillator-induced jitter for the crystal oscillators associated with a cesium-beam frequency standard would be large enough to induce a receiver to lose lock. Obviously, a reference oscillator with a short-erm Allan deviation characteristic that is more than an order of magnitude worse than this example will cause PLL tracking problems, as the data in Tables II-V indicate. In this case, it would depend on the magnitude of other forms of contributing jitter, such as thermal noise and vibration-induced jitter. For the WAAS Reference Station receivers, vibration jitter should not be a large factor, since the receivers are located in a relatively benign environment. It should be kept in mind that some tracking loop disturbances could be tolerated if the tracking loop bandwidth is large enough to track these disturbances. For high quality crystals there should never be a problem of oscillator-induced jitter causing loss of lock in a GPS receiver.

It should also be pointed out that a frequency-locked loop (FLL) is very insensitive to oscillator-induced jitter. Some receivers derive delta range measurements from a receiver carrier-tracking loop operating in FLL. However, these measurements are about an order of magnitude (or more) less accurate than from a PLL. The best solution, as pointed out in [8], is an FLL-assisted PLL.

CONCLUSIONS

It is obvious that poor crystals should not be used with narrow bandwidth systems. However, the user must exercise caution in putting together a system that includes atomic frequency standards. The user must carefully investigate the performance of the crystal that is being used within the atomic standard. The user must learn its short-term characteristics. The user must also investigate the thermal noise characteristics of the receiver that is being used and also investigate the environmental conditions in which the receiver will be located. Otherwise, it is likely that the user's receiver will occasionally lose lock.

Other system characteristics must also be investigated that have not been considered here. It should be pointed out that problems might arise when the carrier-to-noise power ratios (C/N_0) decrease toward the thermal noise threshold.

In conclusion, the design of modern codeless receivers operate at a significantly reduced signal-to-noise ratio (SNR), which requires the tracking loop bandwidths to be extremely narrow [7]. Oscillator instability can be a significant factor and must be considered. The oscillator specification for Allan deviation is important for all receiver designs and must not be overlooked or assumed.

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Additional Readings

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Questions and Answers

HUGO FRUEHAUF (Zyfer, Inc.): You are speaking of the receivers at the WAAS stations, are you?

WILLIAM KLEPCZYNSKI: Yes.

FRUEHAUF: You're not speaking of general GPS receivers.

KLEPCZYNSKI: Well, I think in general, we couldn't do that.

FRUEHAUF: But your narrow bandwidth front end is the WAAS receiver?

KLEPCZYNSKI: Right. This is the one specifically for the WAAS receiver. But that is something I keep in mind because you go to the ION meetings, and they start talking about receivers, narrowing the bandwidth of the receivers, for all sorts of reasons, other reasons other than for simulations. But they should have to keep in mind the stability.